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# DESCENT INTO PLANETARY ATMOSPHERES

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## Introduction

For the first time in the history of cosmonautics the descent module of the Soviet automatic station "Mars-3" made a soft landing on Mars. This was on 2 December 1971 after separation from the "Mars-3" station. The descent module entered the planetary atmosphere, made a descent by parachute, and made a soft landing in the southern hemisphere between the regions of Elektris and Phaetonis in a region with the coordinates 45°S and 158°W. The apparatus carried an emblem with the image of the coat of arms of the Union of Soviet Socialist Republics. The Soviet "Mars-2" and "Mars-3" automatic stations are in the orbits of artificial Martian satellites. The new and outstanding attainment of Soviet cosmonautics affords broad prospects for the further study of planets of the solar system by means of automatic vehicles.

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The most important direction in the Soviet program for the exploration and exploitation of space is the study of the planets of the solar system by means of automatic interplanetary stations. The launchings of the automatic stations "Venera-4, 5, 6 and 7" made it possible for the first time to carry out direct investigations in the Venusian atmosphere and to obtain unique information concerning its temperature, pressure, and chemical composition.

During the first stages the study of celestial bodies is usually conducted from fly-by trajectories. Methods of exploration based on the putting of automatic vehicles into artificial satellite orbits, measurements directly in the atmosphere, landings on the surface, and delivery of the research

results to earth are gradually assuming greater importance. This is becoming possible due to the successive, successful solution by Soviet cosmonautics of many complex scientific and technical problems associated with the creation of automatic stations and their delivery to the planets. One of these is the descent of vehicles into planetary atmospheres.

Now we will examine the solution of this problem applicable to Venus and Mars. Venus has a very dense and Mars has an extremely rarefied atmosphere.

Before sending a space vehicle to any planet it is necessary to analyze the results of its study from the earth by all available means. It is particularly important to know everything which pertains to the atmosphere of a planet because its properties in many respects are determined by the design of the apparatus and its flight program.

For every planet surrounded by an atmosphere one can arbitrarily discriminate the boundary of the dense layers. It is situated at the maximum altitude at which the aerodynamic force of deceleration of the descent module becomes commensurable with the force of planetary attraction. During the flight of a space vehicle above this boundary it can be assumed that the aerodynamic force exerts no influence on its motion. The characteristics of the exoatmospheric segment completely determine the conditions for entry of the space vehicle into the dense layers of the atmosphere: entry velocity $V_{en}$, angle of the velocity vector to the local horizon $\theta_{en}$, and the coordinates of the entry point. The success of the launching is dependent to a large extent on adherence to the initial conditions, whose formation already begins during departure of the space vehicle from an artificial earth satellite orbit. It must be remembered that whereas the entry angle can be virtually any value, the entry velocity is almost completely predetermined by the selected flight program.

Among the numerous ballistic programs for interplanetary flights it is possible to discriminate two principal classes. Direct descent programs provide for the launching of a space vehicle to a planet from an artificial earth satellite orbit with entry into a trajectory hyperbolic relative to the earth and subsequent flight in a transitional ellipse between the earth's orbit and the orbit of the planet of destination. In the planetary sphere of attraction the spaceship moves in a hyperbola and descends to its surface.

Orbital-descent programs differ from direct descent programs in that the space vehicle is shifted from a hyperbolic trajectory into the orbit of an artificial planetary satellite; then the planetary complex descends onto the planetary surface.

Analysis of the flight trajectories reveals that in a direct descent the range of entry velocities is 11-13 km/sec for Venus and 5-8 km/sec for Mars. With descent from circumplanetary orbits the admissible entry velocities decrease to 10.2-7.25 and 3.5-4.7 km/sec respectively.

Another important characteristic applying to the initial conditions for an atmospheric descent is the width of the navigation entry corridor.

The real spacecraft flight trajectory differs somewhat from the computed trajectory. Trajectory corrections are therefore necessary. The accuracy of correction and therefore the accuracy in guiding the space vehicle into the planetary atmosphere both determine the width of the navigation entry corridor.

For the time being it is customary to ensure a relatively low accuracy in guiding a space vehicle in remote space. During flight to Mars and Venus ground facilities guide the spacecraft only to the planetary disk.

If the ship is at a considerable distance from the earth and is in the neighborhood of another planet the self-contained systems can make navigation measurements more precisely. In this case the position of the space vehicle and its trajectory relative to the planet can be determined with an accuracy of a few hundred kilometers. Thus, the conditions for spacecraft entry into the dense layers of the planetary atmosphere are dictated by the choice of the ballistic system and the accuracy in correcting the interplanetary trajectory.

The aerodynamic method of deceleration for extinguishing the energy of space vehicles descending onto the surface of planets surrounded by an atmosphere makes it possible to obtain a considerable energy gain in comparison with a purely active deceleration method.

What are the peculiarities of aerodynamic descent of space vehicles in the atmospheres of Venus and Mars?

It was noted above that at the present time the in-flight guidance of the station to the planetary disk is ensured. With incidence on the center of the disk the entry

angles are close to 90°. Figure 1 shows the dependence of the maximum accelerations $n_{x\ max}$ and the temperatures of heating of the surface of a descent module entering the Venusian atmosphere on the entry angle $\theta_{en}$. The maximum accelerations can attain 400-450 g and the maximum temperatures behind the shock wave arising in front of the descent module can exceed 10 000° C. Even in the case of frontal entry the braking properties of the atmosphere are so great that the vehicle at a distance of several tens of kilometers from the planetary surface cuts its velocity down to 100-200 m/sec. With such velocities this makes it possible to employ a subsonic parachute system for a soft landing similar to that which was employed successfully in returning vehicles of the "Vostok," "Soyuz," "Zond," "Apollo," and others. Accordingly, it can be said that the problem of a soft landing on Venus and other planets with a thick atmosphere does not involve essential difficulties from the ballistic point of view.

It should be noted that the maximum accelerations can be reduced considerably by reducing the angles of entry into the dense layers of the atmosphere (see Fig. 2). However, at the same time there is a considerable increase in the weight of the descent module thermal shielding. It was found that although the maximum temperatures on the descent trajectory decrease with a decrease in the entry angles, this decrease is inadequate for the temperatures to be withstood by any heat-resistant construction material. In such cases one must have recourse to a sublimating covering for thermal shielding. However, the weight of such a covering increases with an increase in the descent time.

Specialists were faced with a dilemma in creating the descent modules for the "Venera" automatic interplanetary stations: either to decrease the acceleration, but at the same time complicate the station by the introduction of an autonomous navigation system and worsen the spacecraft thermal regime, or ensure the performance of the vehicle after exposure to enormous accelerations, dispensing with additional systems, and thereby increase the probability of a successful solution of the problem. Soviet scientists adopted the second approach and actual experience completely confirmed the correctness of the adopted decisions.

Figure 2 shows that the trajectory parameters change very rapidly during descent into the Venusian atmosphere. The velocity is extinguished in only a few seconds from great initial values ($V_{en} \sim 11$ km/sec) to 0.2-0.3 km/sec. The accelerations increase and then very sharply fall off. Already at altitudes of 40-50 km they disappear and this is followed by an

equilibrium dropoff with a relatively low velocity which is still further decreased during opening of the braking parachute.

During descent by parachute the velocities of falling are relatively small (only tens of meters in the initial segment of the parachute fall). During this time different measurements are made and all the collected information is transmitted to earth for processing and analysis. So it happened during the descent of the "Venera" automatic interplanetary station.

Atmospheric density is one of the important parameters. Refined vertical density profiles must be constructed for further design work. Indeed, the density, braking properties of the atmosphere determine virtually entirely the appearance of the descent module (design, strength, ballistic characteristics, etc.). Atmospheric density can be determined indirectly from the known temperature and pressure values tied into altitude above the planetary surface. The measurement of these parameters, however, on the basic deceleration segment is virtually impossible and occurs in the segment of parachute descent which begins only at an altitude of approximately 50 km. For the higher layers one must extrapolate the results. The boundary of the dense layers of the Venusian atmosphere falls at an altitude of 100-125 kilometers above the planetary surface and therefore a rather extended segment is subject to extrapolation. Designers encountered great theoretical difficulties in solving this problem since no reliable data are available on the initial conditions of descent, on the dynamic characteristics of the apparatus, etc. Accordingly, it is desirable that the initial altitude of parachuting be increased.

Now we will discuss the peculiarities of descent of space vehicles in the Martian atmosphere. As is well known, the aerodynamic deceleration method gives a considerable energy gain in comparison with the purely active deceleration and landing method. In this respect a descent onto the Martian surface is no exception. But here a series of specific difficulties arises. In particular, one must mention the extraordinary rarefaction of the Martian atmosphere. With a steep entry of the vehicles into the planetary atmosphere even with a moderate load on the frontal surface ($P_x$ = 200-300 kg/m$^2$) the aerodynamic braking removes only 1.0-2.0 km/sec when the initial entry velocity is 5-6 km/sec. Accordingly, it is necessary to strive toward the maximum effectiveness of the aerodynamic drag. It can be attained by a precise adherence to the initial conditions for entry into the atmosphere, creating a descent module with a small load on the frontal surface, and using vehicles having lift.

"Mars-2"

Launching date ... 19 May 1971
Flight duration ... 192 days
Distance covered ... about 470 million kilometers
Date put into artificial Martian satellite orbit ... 27 November 1971
Orbital parameters of artificial Martian satellite:
maximum distance from planetary surface at apocenter ... 25 000 km
minimum distance from planetary surface at pericenter ... 1380 km
orbital inclination to plane of Martian equator ... 48°54'
period of revolution ... 18 hours 00 minutes

"Mars-3"

Launching date ... 28 May 1971
Flight duration ... 188 days
Date put into artificial Martian satellite orbit ... 2 December 1971
Orbital parameters of artificial Martian satellite:
minimum distance from planetary surface at pericenter ... 1500 km
period of revolution ... about 11 days

Figure 3 shows the dependence of the final velocity ($H_{fin}$ = 5 km) on the entry angle for vehicles of the ballistic type with an identical aerodynamic quality experiencing loads of different magnitude on the frontal surface. The entry velocity was 6 km/sec. It is easy to see that even with deviation by 3-4° from the computed entry angle only those vehicles of the ballistic type can be slowed to a velocity of 0.5-0.7 km/sec which have a load on the frontal surface of not more than 50-60 kg/m$^2$. This is an exceedingly small value. However, the weight of the payload delivered to the planetary surface by such vehicles is considerably less than by vehicles with great frontal loads. The increase in the admissible load on the frontal surface is important, it is one of the central problems in engineering and ballistics in aerodynamic descent of space vehicles on Mars. Its solution requires answers related to the soft landing of a descent module. In particular, one must select a descent program, ascertain the degree to which lift will participate in the descent, solve the problem of descent module control, decide on the landing method, the accuracy of atmospheric entry, and decide on the descent control system, etc.

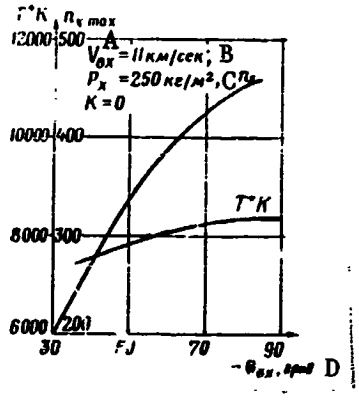


Fig. 1

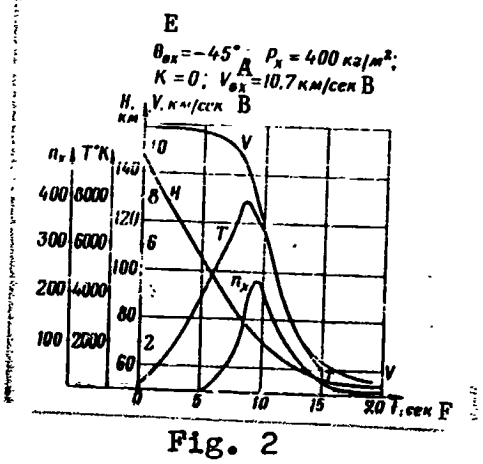


Fig. 2

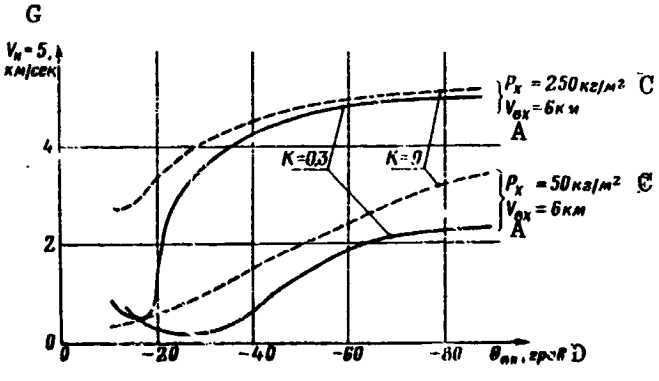


Fig. 3

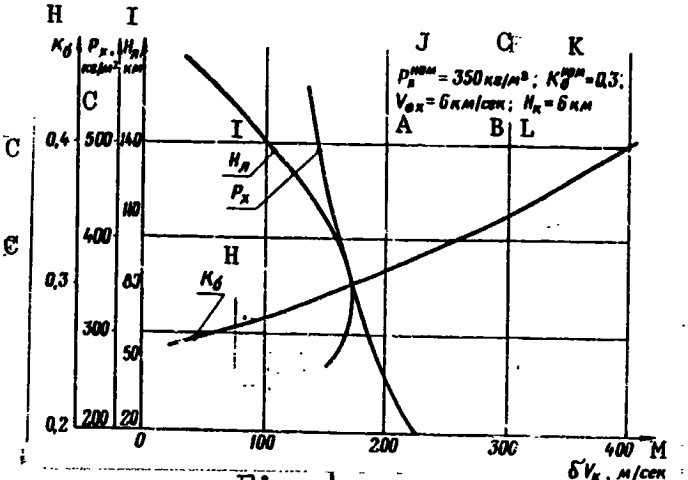


Fig. 4

Annotations: T°K -- gas temperature beyond the compression jump; $n_x$ -- axial overloads acting on descent module; $\theta_{en}$ -- angle of atmospheric entry; $P_x$ -- load on frontal surface of vehicle; K -- aerodynamic quality of flight vehicle; $V_{en}$ -- velocity of atmospheric entry; H -- flight altitude above planetary surface; $t_{en}$ -- time reckoned from initial moment of atmospheric entry; $V_H$ -- flight velocity at altitude H above planet; $K_b$ -- aerodynamic quality of vehicle with balanced angle of attack; $H_p$ -- altitude of nominal pericenter of entry trajectory. A) $V_{en}$; B) km/sec; C) kg/m$^2$; D) $\theta_{en}$, degrees; E) $\theta_{en}^{nom}$; F) t, sec; G) $V_H$ = 5 km/sec; H) $K_b$; I) $H_p$; J) $P_x^{nom}$; K) $K_b^{nom}$; L) $H_{fin}$; M) m/sec

For aerodynamic braking in the Martian atmosphere in the case of a ballistic descent or in the case of descent with lift it is not adequate to guide the spacecraft to the planetary disk. The spacecraft must carry a self-contained navigation system. The precise entry into the planetary atmosphere ensured by this system, in combination with lift control in the atmospheric descent segment, makes it possible to achieve a substantial decrease in the final descent velocity (by several hundred meters per second) in comparison with descent of a space vehicle with a constant aerodynamic quality. We will cite an example for a more graphic estimate. In order for a vehicle weighing 10 tons to extinguish (using its braking engine) its velocity by several hundred meters per second it is necessary that several tons (!) of fuel be burned. However, the additional weight of the system for regulating control is only a few tens of kilograms. Nevertheless, as can be seen from Fig. 4, even in the case of a controlled descent the final velocity of the vehicles is too great.

In order to achieve a soft landing of a descent module on a planetary surface the descent velocity must finally be extinguished to zero by means of a special landing system. It is virtually impossible to obtain a zero final velocity during landing by using only aerodynamic braking. For example, during descent into the Venusian atmosphere the final velocity without use of a soft landing system is within the range of several tens of meters per second, whereas in landing on Mars it is not less than several hundred meters per second.

There are many types of soft landing systems: supporting rotor (of the helicopter type), parachute-reactive, reactive and aircraft.

On planets with a rarefied atmosphere for the descent of vehicles with a low weight one can use parachute-reactive landing, but for heavy vehicles it is best to make use of an engine.

The problems discussed above by no means fully cover the problem of descent into the atmosphere and landing on planetary surfaces. One must also solve a series of highly complex problems associated with determination of the configuration of the descent modules, the type of heat-insulating and heat-regulating systems, the choice of heat-insulating and construction materials, and many others. The soft landing of the descent module on the Martian surface revealed that Soviet science and engineering have successfully solved these complex problems.